

Swift 1644+57: The Longest Gamma-ray Burst?

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21 January 2013

ABSTRACT

Swift recently discovered an unusual gamma-ray and x-ray transient (Sw 1644+57) that was initially identified as a long-duration gamma-ray burst (GRB). However, the ~ 10 keV x-ray emission has persisted for over a \sim month with a luminosity comparable to its peak value. The astrometric coincidence of the source with the center of its host galaxy, together with other considerations, motivated the interpretation that Sw 1644+57 was produced by an outburst from a $\sim 10^{6-7} M_{\odot}$ black hole at the center of the galaxy. Here we consider the alternate possibility that Sw 1644+57 is indeed a long-duration GRB, albeit a particularly long one! We discuss the general properties of very long-duration, low-power GRB-like transients associated with the core-collapse of a massive star. Both neutron star (magnetar) spindown and black hole accretion can power such events. The requirements for producing low-power, very long-duration GRBs by magnetar spindown are similar to those for powering extremely *luminous* supernovae by magnetar spindown, suggesting a possible connection between these two unusual types of transients. Alternatively, Sw 1644+57 could be associated with the *faintest* core-collapse explosions: the collapse of a rotating red supergiant in a nominally failed supernova can power accretion onto a solar-mass black hole for up to ~ 100 days; the jet produced by black hole accretion inevitably unbinds the outer envelope of the progenitor, leading to a weak $\sim 10^{49}$ erg explosion. In both neutron star and black hole models, a jet can burrow through the host star in a few days, with a kinetic luminosity $\sim 10^{45-46}$ erg s⁻¹, sufficient to power the observed emission of Sw 1644+57.

Key words: gamma rays; bursts; supernovae; stars; neutron

1 INTRODUCTION

Sw 1644+57 was detected by the Burst Alert Telescope (BAT) onboard *Swift* on March 28, 2011 (Burrows et al. 2011; Levan et al. 2011). Followup observations with the X-ray Telescope detected a bright point source a few hours later. Unlike essentially all other gamma-ray bursts (GRBs), however, Sw 1644+57 re-triggered BAT three additional times in the first two days. Moreover, the X-ray emission associated with Sw 1644+57 has persisted for more than a month at $L_X \sim 10^{47}$ erg s⁻¹ (isotropic); and although the emission is highly variable on timescales of minutes to days, it is not clear that it is fading significantly in time. This is very different from both short and long-duration GRBs, making Sw 1644+57 unique amongst extragalactic gamma-ray transients.

The host galaxy of Sw 1644+57 is a low mass star-forming ($\sim 0.5 M_{\odot}$ yr⁻¹) galaxy at a redshift of $z = 0.35$ (Levan et al. 2011). There is no evidence for an optical counterpart to the high-energy transient but the near-infrared (NIR) flux faded by a factor of 3 over

~ 5 days, indicating that the transient contributed significantly to the NIR emission, at least at early times (when the X-ray flux was also higher). In addition to the NIR emission, follow-up observations detected Sw 1644+57 in the radio, with the flux brightening by a factor of a few in the first week. NIR astrometry with HST and VLBA observations both determined that Sw 1644+57 is at the center of its host galaxy to within $\sim 0.03''$ or ~ 150 pc (1σ).

The position of Sw 1644+57 relative to the center of its host galaxy, its uniqueness relative to known GRBs, and the qualitative similarity between its spectral energy distribution and those of blazars motivated the interpretation that Sw 1644+57 is powered by a relativistic jet created by accretion onto a $\sim 10^{6-7} M_{\odot}$ black hole at the center of its host galaxy. Moreover, the energetics of the transient, and the reasonably strong limits on pre-outburst emission (e.g., from ROSAT), are broadly consistent with the accretion being powered by the tidal disruption of a solar-type star (Bloom et al. 2011; Burrows et al. 2011).

Although the tidal disruption interpretation of Sw 1644+57 is quite plausible, it is worth exploring alternate explanations of these unique observations. In this *Letter*, we examine the possibility that Sw 1644+57 is in fact a new form of a long-duration GRB; by

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this we mean that the emission is powered by a relativistic outflow created during the core-collapse of a massive star. Our goal in this *Letter* is not to understand all of the observed properties of Sw 1644+57, but rather to assess the zeroth order plausibility of whether it could be associated with the core-collapse of a massive star. In §2 we assess (1) the conditions under which neutron star spindown and/or black hole accretion can power a very long timescale high energy transient (§2.1) and (2) whether low-power jets from a central engine can escape their host star or supernovae ejecta (§2.2). We apply these models to Sw 1644+57 in §3. We conclude by highlighting the many outstanding questions (§4).

2 LOW-POWER GAMMA-RAY BURSTS

2.1 Energetics and Timescales

Low-power outflows (by GRB standards) during the core-collapse of massive stars can be produced by the spindown of a rapidly rotating neutron star (Metzger et al. 2007) or accretion onto a central black hole. A low power does not imply that the event is sub-energetic relative to canonical GRBs, only that the timescale to extract the energy is much longer. Neutron star-powered activity would be associated with a successful core-collapse explosion while black hole accretion could be powered by the infall of the stellar envelope in a failed explosion, or the fallback of material that remains bound during an otherwise successful explosion (Woosley 1993; MacFadyen & Woosley 1999).

A neutron star with a spin period of $1 P_{\text{ms}}$ ms and a magnetic field strength of $10^{14} B_{14}$ G has a rotational energy of $E_{\text{rot}} \simeq 2 \times 10^{52} P_{\text{ms}}^{-2}$ ergs, a relativistic dipole spindown power of $\dot{E} \simeq 10^{47} B_{14}^2 P_{\text{ms}}^{-4}$ erg s $^{-1}$ and a spindown timescale of $t_{\text{spindown}} \simeq 2 B_{14}^{-2} P_{\text{ms}}^2$ days. Powering a month-long event with a total energy of $\sim 10^{51-52}$ ergs thus requires $P \sim 1 - 3$ ms and $B \sim 3 \times 10^{13} - 10^{14}$ G. For vacuum dipole spindown, \dot{E} is relatively constant for $t \lesssim t_{\text{spindown}}$ while for $t \gtrsim t_{\text{spindown}}$, $\dot{E} \propto t^{-2}$. Note, however, that this specific prediction for the temporal power-law index for late-time spindown only applies for a braking index of 3, which is not typically observed for pulsars (e.g., Livingstone et al. 2006).

The timescale for black hole accretion to power central engine activity depends on the rotation and density profiles of the progenitor star and the energy of the explosion (Kumar et al. 2008) – the latter because it determines how much material remains bound to the black hole. In the simplest case of a failed explosion, the timescale on which infall occurs is set by the free-fall time

$$t_{\text{ff}}(r) = \frac{\pi r^{3/2}}{(2GM)^{1/2}} \simeq 702 \left[\frac{r}{10^{14} \text{ cm}} \right]^{3/2} \left[\frac{M(r)}{10 M_{\odot}} \right]^{-1/2} \text{ days.} \quad (1)$$

In order to power a long timescale transient like Sw 1644+57, a weakly bound red supergiant (RSG) progenitor with radius $R > 10^{13}$ cm is required. For a power law density profile, $\rho(r) = \rho_0(r/R)^{-n}$, the enclosed mass $M(r) \propto r^{3-n}$ (for $n < 3$) and the free fall accretion rate is

$$\dot{M}(t) = 4\pi\rho r^2 \frac{dr}{dt_{\text{ff}}} = \frac{2(3-n)}{n} \frac{M}{t_{\text{ff,R}}} \left(\frac{t}{t_{\text{ff,R}}} \right)^{[6/n]-1-n}, \quad (2)$$

where $t_{\text{ff,R}}$ is the free-fall time evaluated at the outer radius. The total power available from stellar infall is thus

$$\dot{E}(t) = \dot{M}c^2 \simeq 6 \times 10^{47} M_{10}^{1/2} R_{14}^{-3/2} \left(\frac{t}{t_{\text{ff,R}}} \right)^{[6/n]-1-n} \text{ ergs s}^{-1}. \quad (3)$$

where the stellar envelope mass is scaled to $10 M_{\odot}$ and the radius to 10^{14} cm $\simeq 10^3 R_{\odot}$. Presumably this energy will be tapped with only fractional efficiency to power a jet, but depending upon the collimation the resulting isotropic equivalent power could be of order

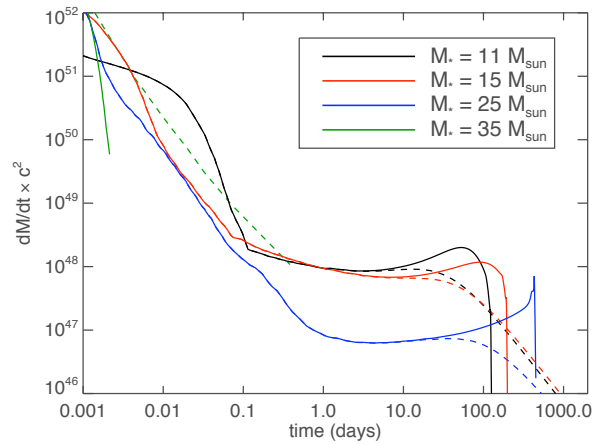


Figure 1. Power available from accretion onto a central black hole for several pre-collapse stellar progenitors from Woosley et al. (2002). The progenitors with initial masses $M \lesssim 30 M_{\odot}$ are red supergiants and the infall of the stellar envelope can power accretion for $\sim 100 - 300$ days. The solid lines assume free-collapse of the entire star, which is quantitatively applicable only if there is either no stellar explosion or a bipolar explosion in which the equatorial region continues to accrete. The dashed lines show the effect of a supernova explosion which resulted in a linear velocity law, $v(r) = v_{\star}(r/R)$, with v_{\star} equal to twice the escape velocity at the surface. For the red supergiant progenitors, this corresponds to a weak explosion with an energy of only $\sim 10^{48}$ ergs.

equation 3 or greater. The actual accretion rate may deviate from the pure free-fall estimate used here since radial pressure support at small radii can slow the infall (Lindner et al. 2010). In addition, the accretion energy depends not only on the infall rate, but also on the angular momentum profile of the progenitor, since only the material that circularizes in a disk will be available to power a jet.

As a concrete example, Figure 1 shows the free fall accretion rate for the non-rotating, solar metallicity pre-supernova progenitor models of Woosley et al. (2002). The models with initial masses $\lesssim 30 M_{\odot}$ are RSGs with radii $R = 0.5 - 1 \times 10^{14}$ cm, while the models with higher masses have lost their hydrogen envelope and have much smaller stellar radii ($R \sim 10^{11}$ cm). The outer density profile for the stars with convective hydrogen layers is shallow and roughly follows a power law with $n = 2$, which gives (eq. 3) a nearly constant accretion rate over the timescale of 200–300 days. The power shuts off very rapidly after this point because the stellar photosphere has been accreted.

If the star undergoes a successful supernova explosion, the accretion onto a central black hole at late times depends on how much material remains bound. The escape velocity for a RSG is only $v_{\text{esc}}(R) = 50 - 100$ km s $^{-1}$; thus even a weak (spherical) explosion can unbind the outer hydrogen envelope and limit the late time accretion. For the layers that do remain bound, material reaches a turnaround radius $r_t = r/[1 - v^2/v_{\text{esc}}^2]$, and then falls back on a timescale $t_{\text{ff}}(r_t)$. In Figure 1, we show how including a linear velocity profile of the form $v(r) = v_{\star}(r/R)$ modifies the late-time accretion power.¹ For expansion at $v_{\star} = 2v_{\text{esc}}(R)$, the accretion rate remains constant until $t \approx 50$ days, and then declines as a power law. For expansion velocities much larger than this, the power drops off at yet earlier times < 1 day. Thus to explain the long duration

¹ In reality, the supernova shock will also alter the density distribution of the star; this effect has been neglected here.

of Sw 1644+57 within the context of black hole accretion, a RSG must have undergone the weakest of explosions, or none at all.

2.2 Interaction with the Host Star

Standard long-duration GRBs have durations ~ 1 minute and are associated with Type Ibc supernovae (Woosley & Bloom 2006). These two facts are not unrelated: the compact stripped progenitors associated with Type Ibc supernovae are the only progenitors in which a jet can escape its host star on a timescale comparable to the duration of the GRB itself (Matzner 2003). We now consider the same reasoning but applied to much lower power jets.

A jet with a momentum flux \dot{P}_j has an associated kinetic power of $L_j = \dot{P}_j v_j$, where v_j is the velocity of the jet material. If the jet interacts with an ambient medium of density ρ_a , the speed of the head of the jet through the ambient medium v_h can be estimated by considering the balance between the momentum flux of the jet and the ram pressure of the ambient medium $\rho_a A_j v_h^2$ (Begelman & Cioffi 1989; Matzner 2003), where $A_j \sim \pi \theta_j^2 r^2$ is the surface area of the head of the jet and θ_j is the jet's opening angle. This yields:

$$v_h \simeq \left(\frac{L_j/A_j}{\rho_a v_j^3} \right)^{1/2} v_j \simeq \left(\frac{L_i/c^3}{4\pi r^2 \rho_a} \right)^{1/2} c \quad (4)$$

where $L_i \simeq 4L_j/\theta_j^2$ is the isotropic equivalent kinetic power in the jet and in the second equality we have assumed that the jet is relativistic. Equation 4 implies $v_h \sim 0.007 L_{i,48}^{1/2} M_{10}^{-1/2} R_{14}^{1/2} c$ where L_i is scaled to $10^{48} \text{ erg s}^{-1}$, which is appropriate for $L_j \sim 10^{45-46} \text{ erg s}^{-1}$ and $\theta_j \sim 3 - 10 \text{ deg}$.

As the head of the jet propagates through the star (and/or supernova ejecta), a cocoon of shocked stellar and jet material forms around the jet. This cocoon in turn drives a lateral shock into the ambient medium. The speed of this lateral shock v_l can be estimated by balancing the pressure in the cocoon with the ram pressure of the lateral shock. Since the jet produced by a central magnetar and/or black hole accretion disk is very likely to be magnetized, the same applies to the cocoon. The toroidal magnetic field in the cocoon in turn creates an asymmetric pressure distribution, with the pressure being much larger near the jet axis than at large cylindrical radii (Begelman & Li 1992). This reduces the lateral expansion speed of the cocoon. To account for this, we estimate the pressure in the cocoon that drives the lateral expansion as $p_c \simeq fE/(3V)$ where E is the total energy supplied by the central engine up to the time of interest, V is the volume of the cocoon, and the factor $f < 1$ accounts for the pinching effect of the toroidal magnetic field. The speed of the lateral shock driven by the cocoon is thus $v_l \simeq v_h f^{1/4} \theta_j^{1/2} (c/v_h)^{1/4}$.

We now consider the limit in which the timescale for the jet to escape the surrounding star is short compared to the expansion time of the stellar envelope. This is appropriate, e.g., for a failed supernova explosion, as in the supergiant collapse scenario considered in §2.1. In this case, the time for the jet to escape the progenitor is

$$t_{esc} \simeq 5 L_{i,48}^{-1/2} M_{10}^{1/2} R_{14}^{1/2} \text{ days (no expansion)} \quad (5)$$

The corresponding lateral speed of the cocoon-driven shock is

$$v_l \simeq 0.3 v_h \left(\frac{f}{0.03} \right)^{1/4} \left(\frac{\theta_j}{3 \text{ deg}} \right)^{1/2} \left(\frac{v_h}{0.01 c} \right)^{-1/4} \quad (6)$$

where we have scaled the reduction factor f to a value appropriate if the magnetic energy in the cocoon is comparable to the thermal energy (e.g., Fig. 3 of Bucciantini et al. 2007). Equation 6 implies that the lateral expansion time ($\sim [\pi/2][R/v_l]$) is a factor of ~ 5 longer than the time it takes the jet to escape the star, even for the

low power jets of interest here. It is thus plausible that the jet can escape the star before the cocoon completely envelops the stellar envelope. Once the jet escapes the star, the material in the cocoon, which has a sound speed $\sim c/\sqrt{3} \gg v_l$, will escape along with the jet, depressurizing the cocoon. After the cocoon depressurizes, the lateral shock will decelerate as it sweeps up mass, reaching a velocity of order $v_{lf} \sim (2E_c/M)^{1/2}$, where $E_c \sim fL_j t_{esc}$ is the energy acquired prior to breakout. The timescale for the lateral shock to propagate completely around the star is then

$$t_{env} \simeq 70 L_{i,48}^{-1/4} M_{10}^{1/4} R_{14}^{3/4} \left(\frac{f}{0.03} \right)^{-1/2} \left(\frac{\theta_j}{3 \text{ deg}} \right)^{-1} \text{ days.} \quad (7)$$

The energy of the lateral shock $\sim fL_j t_{esc}$ exceeds the binding energy of the envelope of a supergiant progenitor ($\sim 10^{48} \text{ ergs}$) if $t_{esc} \gtrsim 0.4 (f/0.03)^{-1} L_{j,45}^{-1} \text{ days}$, where the total jet power is scaled to $10^{45} \text{ erg s}^{-1}$. This inequality also applies at each radial shell within a given progenitor. Thus, once the head of the jet reaches the radius r where $t_{esc}(r) \gtrsim 0.4 (f/0.03)^{-1} L_{j,45}^{-1} \text{ days}$, the remaining outer envelope of the star is unbound, with an energy $\sim 10^{49} L_{i,48}^{1/2} M_{10}^{1/2} R_{14}^{1/2} (\theta_j/3 \text{ deg})^2 (f/0.03) \text{ ergs}$. For our fiducial parameters, matter is unbound outside $\sim 10^{13} \text{ cm}$. Matter at smaller radii can, however, continue to infall onto the central black hole. The maximum timescale over which infall can proceed without being strongly affected by the expulsion of the envelope is

$$t_{ff,max} \sim 70 \left(\frac{f}{0.03} \right)^{-1} \left(\frac{\theta_j}{3 \text{ deg}} \right)^{-2} L_{i,48}^{-1/2} \text{ days} \quad (8)$$

where we have used the fact that the density profile at large radii in supergiants is $\rho(r) \propto r^{-2}$. These order of magnitude arguments suggest that the collapse of a RSG could potentially power jets for up to ~ 100 days. One uncertainty in these estimates is how much of the star at small radii $\lesssim 10^{10-11} \text{ cm}$ falls directly into the black hole vs. circularizes in a disk; this matter can in principle produce large jet powers at early times $\lesssim 1000 \text{ sec}$ (Fig. 1), which might more readily unbind the outer stellar envelope. We have assumed that most of this mass instead forms the initial black hole.

We now consider the case of a successful stellar explosion, in which the stellar envelope expands outwards with a velocity $v_{ej} \sim 10,000 \text{ km s}^{-1}$. In this case the head of the low power jet initially cannot keep up with the expansion induced by the stellar explosion. As the stellar density decreases due to expansion the velocity of the head of the jet increases, reaching $v_h \sim v_{ej}$ when $R \sim (4Mc^3)/(L_i)(v_{ej}/c)^2$; using $R \simeq v_{ej} t$ for the expanding ejecta, this implies that the jet can escape the ejecta at a time t_{esc} given by

$$t_{esc} \simeq \frac{4v_{ej}Mc}{L_i} \simeq 30 \frac{v_{ej,9}M_{10}}{L_{i,48}} \text{ days (envelope expansion).} \quad (9)$$

where $v_{ej,9}$ is the velocity of the supernova ejecta in units of $10,000 \text{ km s}^{-1}$. Equation 9 does not apply to standard long-duration GRBs, for which the jet escape time is shorter than the expansion time of the stellar envelope. In the latter case equation 5 is the correct estimate of the jet escape time even if the explosion is successful.

If the central engine remains active for a duration $\gtrsim t_{esc}$ then the jet can escape the surrounding stellar ejecta, potentially powering a high energy transient. For a black hole central engine in a supergiant progenitor, the infall time of the stellar envelope (see Fig. 1) is longer than the escape time in either a failed or weak explosion (eqs. 5 & 9). However, because the outer envelope of a red supergiant has a binding energy of only $\sim 10^{48} \text{ ergs}$, it is easily disrupted. In particular, equation 7 shows that the lateral expansion of the cocoon-driven shock will eventually envelop the stellar

envelope and unbind it, stifling accretion at smaller radii. For sufficiently collimated and/or magnetized jets, however, accretion fed by the infall of the stellar envelope can last for a duration approaching the free-fall time of the outer envelope ~ 100 days (eq. 8).

For a spinning down magnetar, the requirement that $t_{\text{esc}} \lesssim t_{\text{spindown}}$ in a successful explosion can be shown to imply that the magnetar jet must be sufficiently collimated in order to escape the surrounding ejecta while most of the spindown power remains: $\theta_j \lesssim 10 (v_{ej9} M_{10})^{-1/2}$ deg. Initially, most of the energy flux in a neutron star outflow is in the equatorial plane of the rotator. However, the outflow's toroidal magnetic field builds up outside the termination shock and can collimate the outflow into a jet along the polar axis (Bucciantini et al. 2009). Numerical simulations in the long-duration GRB context yield collimation angles $\lesssim 10$ deg. However, the degree of collimation, i.e., θ_j , depends sensitively on the magnetization in the region between the termination shock and the bulk of the supernova ejecta (as in the cocoon dynamics described above eq. 5). This is difficult to predict with certainty. If the jet cannot escape the stellar ejecta it is plausible that the spindown power of the magnetar is instead thermalized, heating the ejecta and potentially powering an ultra-luminous supernova (Kasen & Bildsten 2010). Even if the jet does escape, the fact that the escape and spindown times are comparable suggests that some of the spindown power is likely to be transferred to the stellar envelope, contributing to the luminosity of the supernova.

3 APPLICATION TO Sw 1644+57

The zeroth-order observational requirements for explaining Sw 1644+57 are that a source must produce a relativistic outflow with appreciable power for several weeks with a total energy budget $\sim 10^{50-52}$ ergs; the energy is only loosely constrained because of uncertainties in the beaming. Burrows et al. (2011) argued that the x-ray lightcurve in the first ~ 3 weeks could be broadly reproduced by the $t^{-5/3}$ scaling expected for fallback and/or tidal disruption, but this fading is uncertain and depends on how the luminosity in the observed bands is related to the bolometric luminosity.

The results of §2 demonstrate that both a spinning down neutron star with $P \sim$ a few ms and $B \sim 3 \times 10^{13}$ G and accretion onto a newly formed solar mass black hole can match the energetics and timescale of Sw 1644+57. The reason that Sw 1644+57 is so distinct from more typical long-duration GRBs is, however, fundamentally different in the neutron star and black hole models. In the neutron star model, the required magnetic field strength for Sw 1644+57 is $B \sim 3 \times 10^{13}$ G rather than $B \sim 10^{15-16}$ G as in long-duration GRB models. This increases the spindown timescale by $\sim 4 - 5$ orders of magnitude. By contrast, in the black hole accretion context, the key difference between Sw 1644+57 and standard GRBs would be the stellar progenitor: a red supergiant for Sw 1644+57 versus stripped envelope progenitors for typical long-duration GRBs.

The time it takes the low-power jet associated with Sw 1644+57 to escape the stellar envelope is significantly longer than in typical long-duration GRBs. Nonetheless, given plausible jet powers $L_j \sim 10^{45-46}$ erg s $^{-1}$ and the uncertainty in the collimation, the escape timescale could be as short as a few days (eqs 5 & 9). This is true even for a supergiant progenitor which has a radius of $\sim 10^{14}$ cm. In the context of a successful stellar explosion, the radius of the supernova ejecta at the time of jet 'breakout' would also be $\sim 10^{14}$ cm (even if the progenitor is initially much more compact). It is possible that the \sim few day timescale for the jet to escape imprints itself on the observed lightcurve, accounting for the initial few day peak of activity observed from Sw 1644+57.

The constraints on the Lorentz factor of Sw 1644+57 are not very stringent (perhaps $\Gamma \sim 3 - 10$) relative to typical GRBs because the emission is comparatively soft (Bloom et al. 2011). In the core-collapse context it is possible that Sw 1644+57 would be less relativistic than normal GRBs because of additional mixing with the stellar material as the low power jet traverses the star.

In addition to the energetics and duration constraints, Sw 1644+57 showed significant variability on timescales of ~ 100 sec, which Bloom et al. (2011) associated with the dynamical time around the event horizon of a $\sim 10^6 M_\odot$ black hole. This interpretation is very plausible, but it may not be unique. For a solar-mass central engine, one would also expect variability on much shorter timescales, down to milliseconds. The signal to noise in the Sw 1644+57 x-ray light curve is not, however, sufficient to constrain significant variability on $\lesssim 10$ sec (N. Butler, private communication). Moreover, the temporal power spectrum of the *Swift* lightcurve does not show any feature at a particular timescale (e.g., ~ 100 sec) and is instead consistent with a power-law that reaches the noise floor for $\lesssim 10$ sec (see Fig. S1b of Bloom et al. 2011). Given that GRBs, AGN, and X-ray binaries all have roughly power-law temporal power spectra, it is not clear that the variability of Sw 1644+57 clearly favors one central engine over another. More quantitatively comparing the temporal power spectrum of Sw 1644+57 with these other classes of objects would be very interesting. On the theoretical side, the longer timescale ($\gtrsim 0.1 - 1$ sec) variability in canonical long-duration GRBs may arise primarily due to interaction with the surrounding star (e.g., Bucciantini et al. 2009; Morsony et al. 2010). We would expect the same to be true in the context of Sw 1644+57, although the precise timescales produced by this interaction are likely to change because of the lower jet power and the different progenitor.

4 DISCUSSION

We have argued that models with central engines like those of long-duration GRBs – solar-mass compact objects formed during the core-collapse of a massive star – can explain the broad properties of the unusual gamma-ray transient Sw 1644+57. Specifically, models with solar-mass compact objects produce jets with similar kinetic power and timescales to those invoked in the context of massive black hole accretion in Bloom et al. (2011) and Burrows et al. (2011). The phenomenology of the resulting emission depends largely on the properties of the jet and thus should in many ways be independent of the central nature of the engine, complicating the interpretation of Sw 1644+57.

The localization of Sw 1644+57 to near the center of its host galaxy is highly suggestive of AGN activity, but it is also not unreasonable to suspect that a stellar explosion might occur in the galactic nucleus, perhaps associated with circumnuclear star formation. Long-duration GRBs have a tendency to appear in the brightest star forming regions of a galaxy (Fruchter et al. 2006), which in this case coincides with the center. The offset distributions for GRBs constructed by Bloom et al. (2002) indicate a $\sim 10\%$ probability of finding a GRB within the radius allowed by observations of Sw 1644+57 (i.e., within $\sim 20\%$ of the galaxy half light radius). GRB 021004, for example, was located similarly close (< 119 pc) to its host galaxy center (Fynbo et al. 2005).

In some ways, Sw 1644+57 did not show the expected signatures of a tidal disruption event. In the usual picture, the fallback of bound material forms a disk near the tidal disruption radius and radiates primarily in the ultraviolet/optical (Ulmer 1999). For systems with super-Eddington fallback rates, which are probably the most likely to power relativistic jets, a particularly bright optical

transient is expected associated with outflows driven by radiation pressure (Strubbe & Quataert 2009); there are indeed several recent tidal disruption candidates selected on such optical emission (van Velzen et al. 2010; Cenko et al. 2011). The fact that no such optical transient was seen for Sw 1644+57 could be the result of significant dust extinction ($A_V \sim 10$ mag) in the host galaxy nucleus, which Levan et al. (2011) argue is consistent with the high hydrogen column density determined from the x-ray spectrum. In the magnetar GRB model, high dust extinction would likely also need to be invoked to explain the non-detection of a supernova. On the other hand, in the RSG collapse model the absence of a bright optical transient is to be expected given the failure (or extreme weakness) of the supernova explosion.

Continued monitoring of Sw 1644+57 should help clarify its origin. A prolonged phase of relatively constant x-ray luminosity becomes, at some point, difficult to reconcile with a tidal disruption model. Rather, one expects to see the power decline on the fallback timescale, which is $t_{fb} \sim 20 (M_{BH}/10^6 M_\odot)^{5/2} (R_p/3R_s)^3$ min for a solar type star (where M_{BH} is the black hole mass and R_p is the peribothron distance of the stellar orbit, scaled to 3 Schwarzschild radii). For a $10^6 (10^7) M_\odot$ black hole, $t_{fb} \lesssim 7 (20)$ days unless the disrupted star is a giant with a large radius. For $t \gtrsim t_{fb}$, the jet power should decrease in time, which is not readily apparent in the recent *Swift* data for Sw 1644+57 (though the interpretation is complicated by the difficulty of relating the luminosity in the *Swift* bandpass to the bolometric luminosity, let alone to the jet power or accretion rate). In the magnetar model, the jet power will remain roughly constant for the initial spindown timescale of the neutron star. Depending on the jet collimation and efficiency, the requisite power can be maintained for significantly longer than a month while still satisfying the energy constraints of a maximally spinning neutron star (§2.1). The RSG collapse model predicts a nearly constant jet power for up to ~ 100 days, followed by a rapid drop off (see §2.2 and Fig. 1).

If Sw 1644+57 was in fact of stellar origin, one might ask why its properties were so discontinuous compared to any other GRB observed to date. The magnetar model provides no obvious explanation – presumably a continuous range of magnetic field strengths, and hence spin down rates, could be realized. In the supergiant collapse case, on the other hand, the discontinuity reflects the bimodality of progenitor radii depending on whether or not a massive star retains its hydrogen envelope. Figure 1 demonstrates that this bimodality is in fact predicted in the set of Woosley et al. (2002) progenitors of varying masses. The low rate inferred from Sw 1644+57 suggests that, compared to stripped envelope stars, collapse and relativistic jet production in RSG progenitors is a rare event, if it happens at all.

The large energy injection on week-month timescales required to understand Sw 1644+57 is similar to the energy injection required to power ultraluminous supernovae (e.g., Quimby et al. 2007; Miller et al. 2009) by magnetar spindown (Kasen & Bildsten 2010). Moreover, within the (very large) uncertainties, the rate of ultraluminous supernovae (Quimby et al. 2009) is comparable to the estimated rate of events like Sw 1644+57. It is thus possible that these seemingly different transients are closely related, with neutron star spindown being the central engine in both cases.

If, on the other hand, Sw 1644+57 was powered by black hole accretion from stellar collapse, the outburst may be associated with some of the *faintest* supernovae known. Observations of Type IIP supernovae indicate that the explosion energy achieved in the core collapse of RSGs varies significantly from case to case (Hamuy 2003), including several recorded instances of very weak

mass ejections ($E < 10^{50}$ ergs; Zampieri et al. 2003; Pastorello et al. 2004; Fraser et al. 2010). The luminous red novae are even dimmer transients with inferred explosion energies of order the binding energy of a RSG $\sim 10^{48}$ ergs (Kulkarni et al. 2007; Thompson et al. 2009; Bond et al. 2009). Pre-explosion images of some luminous red novae suggest that the progenitors are relatively massive stars ($M \sim 10 M_\odot$) heavily enshrouded in dust (Prieto et al. 2008). It remains unclear, however, whether these events represent the true core collapse of a star or rather just a pulsational episode that unbinds some of the hydrogen envelope. In any case, given the range of observed outcomes, it seems possible that in some rare circumstances the supernova shock in a RSG envelope might only reach a few times the escape velocity, or fail to develop altogether. Provided the progenitor had sufficient angular momentum, a likely outcome appears to be a GRB of low power and unusually long duration, similar to Sw 1644+57.

ACKNOWLEDGMENTS

We are grateful to J. Bloom, N. Butler, B. Cenko, B. Metzger, D. Perley, and E. Ramirez-Ruiz for very helpful discussions. This research has been supported by the DOE SciDAC Program (DE-FC02-06ER41438). EQ was supported in part by the David and Lucile Packard Foundation.

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